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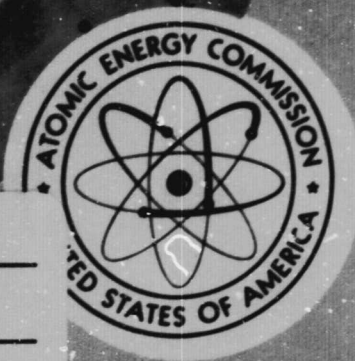
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MASTER

Neutron Physics Division

CALCULATION OF THE RADIATION HAZARD AT SUPERSONIC AIRCRAFT ALTITUDES PRODUCED BY AN ENERGETIC SOLAR FLARE. II.

T. W. Armstrong and H. S. Moran

Abstract

Calculations have been carried out to estimate the absorbed-dose and dose-equivalent rates at various depths in the atmosphere produced by an energetic solar flare - the flare of February 23, 1956. The dose rates are determined both by computing flux spectra using air only and applying flux-to-dose conversion factors and by computing the dose rates in tissue using an air-tissue-air arrangement. The two methods of calculation are in reasonable agreement when the flux-to-dose factors are applied to the forward-flux spectra, but the calculations indicate that previous results obtained using omnidirectional-flux spectra overestimate the dose rates. Also, the effect of the fuel carried by a supersonic aircraft on the dose received by the passengers in the event of a solar flare has been considered and found not to be substantial.

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I. INTRODUCTION

In a previous paper,[1] hereinafter referred to as paper 1, the absorbed-dose and dose-equivalent rates produced in the atmosphere by an energetic solar flare - the flare of February 23, 1956 - were computed. These results were obtained by calculating flux spectra at various atmospheric depths and then applying available flux-to-dose conversion factors to determine the dose rates. This procedure for obtaining the dose rates is, of course, only approximate, and the primary purpose of the present work is to evaluate the validity of this approximation. A second objective is to estimate the influence that the fuel carried by a supersonic aircraft will have on the dose received by the passengers in the event of a solar flare.

Here, as in paper 1, we are concerned with only the maximum dose in a 30-g/cm^2 slab of tissue; that is, the dose rate at a depth of x g/cm^2 in air means the maximum dose rate which would occur in a slab of tissue if the tissue were to replace the air from x to $x + 30$ g/cm^2. Obviously, to determine the dose correctly involves calculating the spatial dependence of the dose in the tissue using an air-tissue-air arrangement with the tissue located at each of the depths at which the dose is desired. However, this procedure requires considerable computational effort since a separate transport calculation must be carried out to determine the dose at each depth. A more expedient procedure, which was used in paper 1, is to compute in a single transport calculation the flux spectra at each depth using air only. These spectra are then multiplied by available flux-to-dose factors, which have been determined using tissue only, to obtain the dose at each depth. This procedure introduces several approximations. In the present work calculations are carried out using an air-tissue-air

arrangement, and the dose in the tissue is compared with that given in paper 1 to obtain the error introduced by using flux-to-dose conversion factors.

In order to interpret subsequent comparisons of the results obtained here with those given in paper 1, it is necessary to point out some of the approximations involved in using flux-to-dose factors and in the manner in which the factors were used in paper 1. The flux-to-dose factors used were determined for the case of monoenergetic neutrons or protons normally or isotropically incident on one side of an infinite slab of tissue 30 g/cm^2 in thickness with a vacuum on either side of the tissue.[b] The application of these factors to any other configuration, including that of interest here where there is air on either side of the tissue, introduces some error. Too, the angular distribution of the flux is, in general, intermediate between the two extremes for which the flux-to-dose factors were determined. Thus there exists some choice as to how the flux-to-dose factors can be implemented. In paper 1 the factors for normal incidence were applied to the omnidirectional flux. It is important to realize also that applying flux-to-dose factors to the spectra calculated using air only cannot yield the same dose which would be obtained using an air-tissue-air arrangement because of the flux perturbation caused by the presence of the tissue; that is, the flux spectrum at a given depth in air is not the same as at an air-tissue interface at this depth because of the difference in the nuclear properties of air and tissue. A further approximation is introduced when using flux-to-dose factors corresponding to the maximum dose because the depth in the tissue at which the maximum occurs is energy dependent. Therefore, multiplying the flux at each energy by the corresponding flux-to-dose

factor at each energy and summing gives the sum of the maximum doses at
each energy, which, in general, is larger than the maximum dose in the
tissue.

In the next section some of the details of the calculation are given,
and in Section III the results are presented and discussed.

II. CALCULATIONAL DETAILS

The calculations have been carried out for the solar flare which took
place on February 23, 1956. This flare was unusual because of the very
large intensity of high-energy protons. Since the energy spectrum for this
flare is not well known, Felsche[5] has estimated upper and lower limits for
the prompt (i.e., for a time near maximal intensity) flux spectrum. In
paper 1 calculations were made for both limits, but in the present calcu-
lations only the upper-limit spectrum is considered. It is assumed that
the proton flux is incident isotropically on the top of the atmosphere.
The flux spectrum used is given in paper 1.

The configurations considered are illustrated in Fig. 1. The protons
are incident at $x = 0$, and the thickness of the atmosphere is taken to be
1033 g/cm^2. The ground was not considered since it will have a negligible
effect at the high altitudes which are of interest here. The configuration
for air only is that used in paper 1, and the configuration with the tissue
at a depth of 58 g/cm^2 (65,000-ft altitude) was chosen to compare with the
results at this depth using air only. Since supersonic aircraft will carry
substantial amounts of fuel, the question arises as to what, if any, effect
the difference in the nuclear properties of fuel and air will have on the
dose received by the passengers. To estimate this effect, a configuration
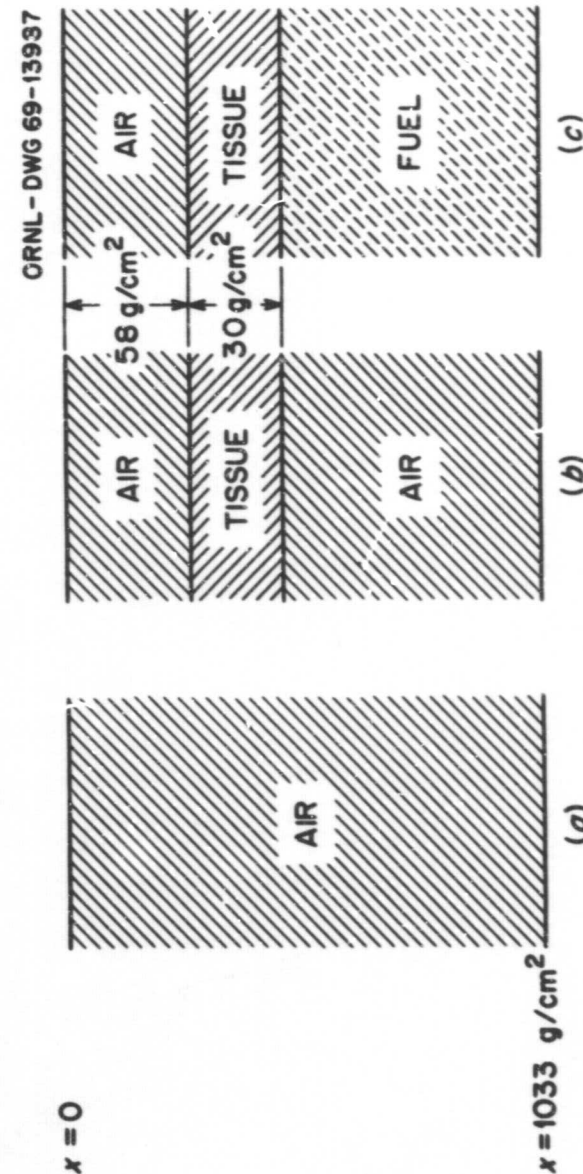was chosen in which the air below the tissue is replaced by fuel. The

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Fig. 1. Configurations Considered.

structural materials of the aircraft have not been included since the calculations of Leimdorfer *et al.*[6] indicate that they will not have a significant effect on the dose inside the aircraft.

The composition of the materials used are given in Table I. The density variation of the air with altitude was taken into account since pions and muons are included in the calculations, and their decay probability per unit distance is density dependent.

As for the method of calculation, the Monte Carlo transport program written by Coleman[9] was used for protons, charged pions, muons, and neutrons above 15 MeV, and the Monte Carlo program of Irving *et al.*[10] was used for neutrons below 15 MeV. The details of the method of calculation are the same as discussed in paper 1 with two minor exceptions: here the coupling energy between the two transport programs is 15 MeV rather than 25 MeV used in paper 1, and here elastic collisions by neutrons above the coupling energy are included whereas they were not in paper 1.

TABLE I

COMPOSITION OF MATERIALS USED
(in atom percent)

Element	Air[a] (Density: variable)	Tissue[b] (Density: 1.00 g/cm^3)	Fuel[c] (Density: 0.80 g/cm^3)
H		62.41	68.0
C		12.23	32.0
N	79.0	1.08	
O	21.0	23.63	
Na		0.04	
Mg		0.01	
P		0.28	
S		0.04	
Cl		0.02	
K		0.03	
Ca		0.23	

a. The density variation with altitude was taken from ref. 7.

b. This is the composition for "whole body" tissue and is based on the data given in ref. 4.

c. The fuel density and composition are based on the data given in ref. 8.

III. RESULTS

Figures 2 and 3 show the absorbed-dose and dose-equivalent rates, respectively, for four cases: (a) the dose rate at various depths taken from paper 1, which were determined by computing the omnidirectional flux spectra at each depth using air only and applying flux-to-dose factors; (b) the dose rate at various depths determined by computing the "forward" flux spectra, i.e., the flux spectra due only to those particles moving downward in the atmosphere, at each depth using air only and applying flux-to-dose factors; (c) the dose rate at the air-tissue interface at 58 g/cm² determined by computing the forward flux at the interface using an air-tissue-air arrangement and applying flux-to-dose factors; and (d) the dose-rate distribution in the tissue, which is the correct dose in the sense that an air-tissue-air arrangement was used and flux-to-dose factors were not used. The error bars on these and subsequent figures represent statistical errors of one standard deviation. It should be noted that it is only the maximum dose in the tissue which is relevant for comparison since the flux-to-dose factors used are those for maximum dose. These comparisons show that the results obtained in paper 1 using the omnidirectional flux give a considerable overestimate of the true dose rate and that a better estimate is obtained when the forward flux is used. The dose rate obtained using the forward flux is essentially the same as in the tissue for the absorbed dose rate but overestimates the dose-equivalent rate by ~ 25%. A breakdown of the dose contribution according to particle type and energy is given in Tables II and III. The omnidirectional and forward spectra for air only and the forward spectrum at the air-tissue interface are given in Figs. 3 and 4 for neutrons and protons, respectively. The reason for the substantial
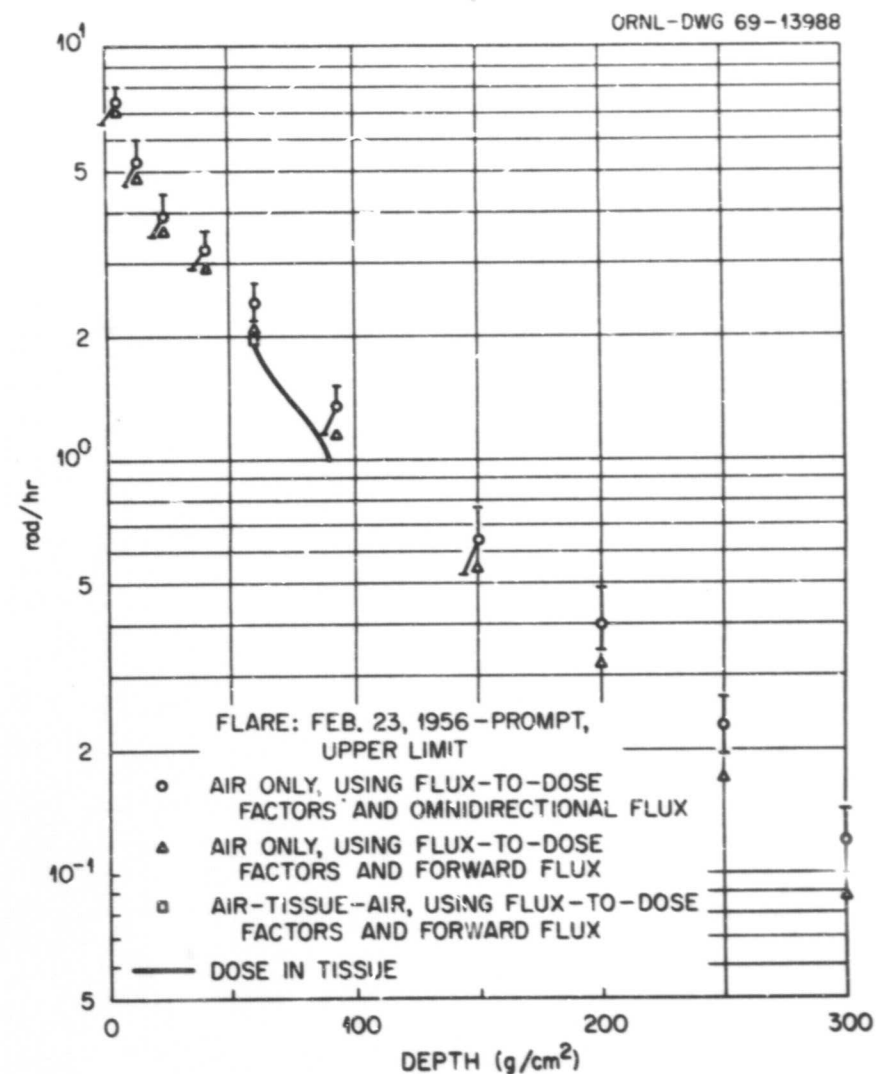
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Fig. 2. Absorbed-Dose Rate vs Depth. The error bars for the dose rates obtained using the forward flux have about the same magnitude as those at the corresponding depth for the omnidirectional case.
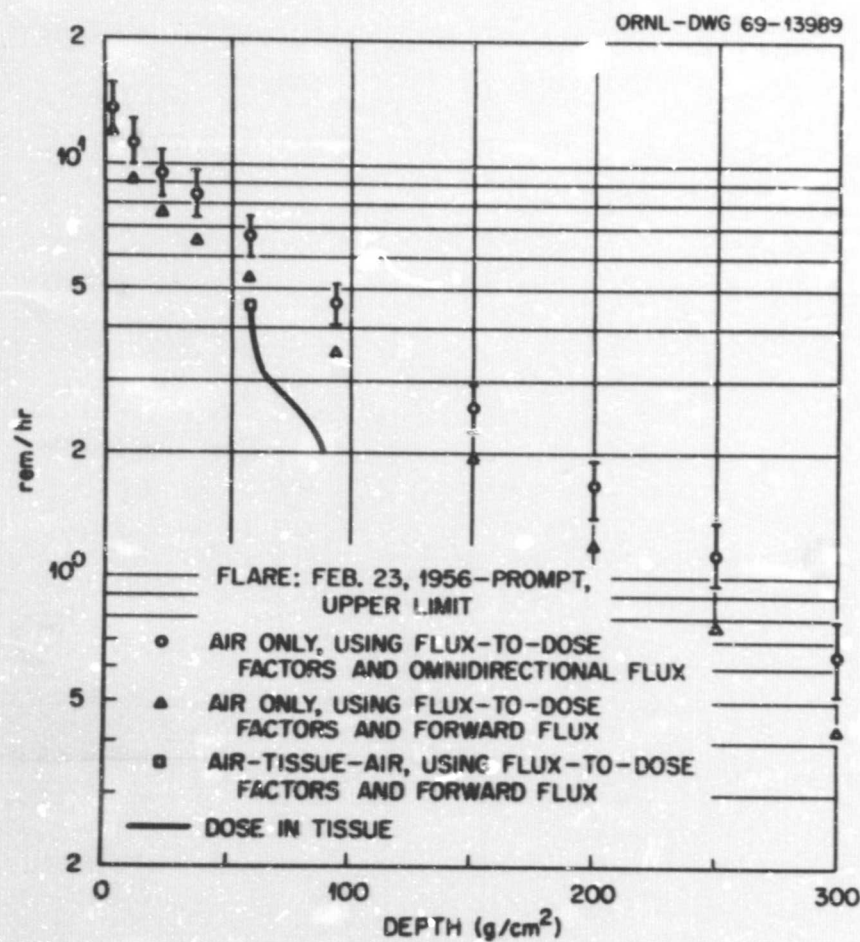
Fig. 3. Dose-Equivalent Rate vs Depth. The error bars for the dose rates obtained using the forward flux have about the same magnitude as those at the corresponding depth for the omnidirectional case.

TABLE II

ABSORBED DOSE RATE (rad/h) AT A DEPTH OF 58 g/cm² USING FLUX-TO-DOSE FACTORS

Particle and Energy Range (MeV)	Air Only, Using Omni-Directional Flux	Percent of Total	Air Only, Using Forward Flux	Percent of Total	Air-Tissue Interface, Using Forward Flux	Percent of Total
Protons, all energies	1.75	73.8	1.63	79.5	1.59	81.6
Neutrons, > 100	0.193	8.1	0.164	8.0	0.163	8.4
Neutrons, 10-100	0.142	6.0	0.108	5.3	0.104	5.3
Neutrons, 1-10	0.137	5.8	0.070	3.4	0.060	3.1
Neutrons, 0.1-1	0.090	3.8	0.048	2.3	0.020	1.0
Neutrons, < 0.1	0.060	2.5	0.030	1.5	0.011	0.6
TOTAL	2.37	100.0	2.05	100.0	1.95	100.0

TABLE III

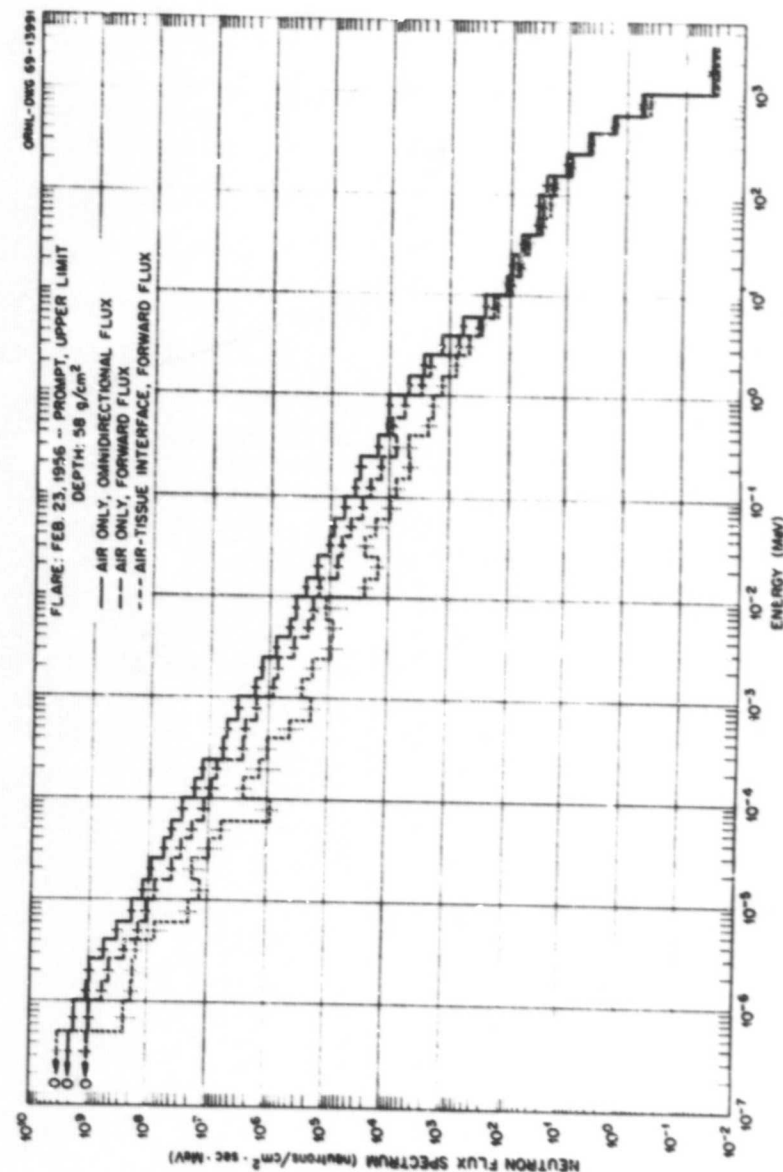…OSE EQUIVALENT RATE (rem/h) AT A DEPTH OF 58 g/cm² USING FLUX-TO-DOSE FACTORS

Particle and Energy Range (MeV)	Air Only, Using Omni-Directional Flux	Percent of Total	Air Only, Using Forward Flux	Percent of Total	Air-Tissue Interface, Using Forward Flux	Percent of Total
Protons, all energies	2.82	41.9	2.67	50.6	2.57	56.8
Neutrons, > 100	0.710	10.5	0.592	11.2	0.634	14.0
Neutrons, 10-100	0.861	12.8	0.664	12.6	0.659	14.6
Neutrons, 1-10	1.22	18.1	0.720	13.6	0.441	9.8
Neutrons, 0.1-1	0.941	14.1	0.545	10.3	0.192	4.2
Neutrons, < 0.1	0.178	2.6	0.090	1.7	0.026	0.6
TOTAL	6.73	100.0	5.28	100.0	4.52	100.0

Fig. 4. Neutron Flux Spectra at a Depth of 58 g/cm². The fluctuations in the low-energy portion of the spectrum with the tissue present are due to poor statistics.

overestimate of the dose equivalent rate when the omnidirectional flux is used is evident from these tables and figures: Most of the absorbed dose is contributed by protons and high-energy neutrons, both of which are moving predominantly in the forward direction, whereas neutrons in the 0.1- to 10-MeV range, which are nearly isotropic and have a high quality factor, contribute appreciably to the dose equivalent.[c]

From Figs. 2 and 3 it is seen that the dose rate determined using the flux spectrum at the air-tissue interface and flux-to-dose factors is in excellent agreement with the dose rate in the tissue. This means that the major error introduced by using flux-to-dose factors and flux spectra computed for air only is due to the neglect of the flux perturbation caused by the tissue. The presence of the tissue is mainly reflected by the changes produced in the neutron spectrum in the 0.1- to 10-MeV range (see Figs. 4 and 5). The tissue has little effect on the proton spectrum or the neutron spectrum above 10 MeV. Although the neutron spectrum below 0.1 MeV is changed significantly, these neutrons do not contribute appreciably to the dose.

The spatial distribution of the dose rates in the tissue shown in Figs. 2 and 3 are given in more detail in Fig. 6. Also shown in Fig. 6 are the dose rates obtained when the air below the tissue is replaced by fuel. The fuel increases the average absorbed-dose rate in the tissue by about 4% and the dose equivalent rate by about 8%; these differences are comparable to the statistical error of the calculation. The influence of the fuel on the neutron-flux spectrum at the back face of the tissue is shown in Fig. 7. Thus, although replacing air by fuel has a marked effect on the low-energy portion of the neutron spectrum, the dose received by the tissue is affected
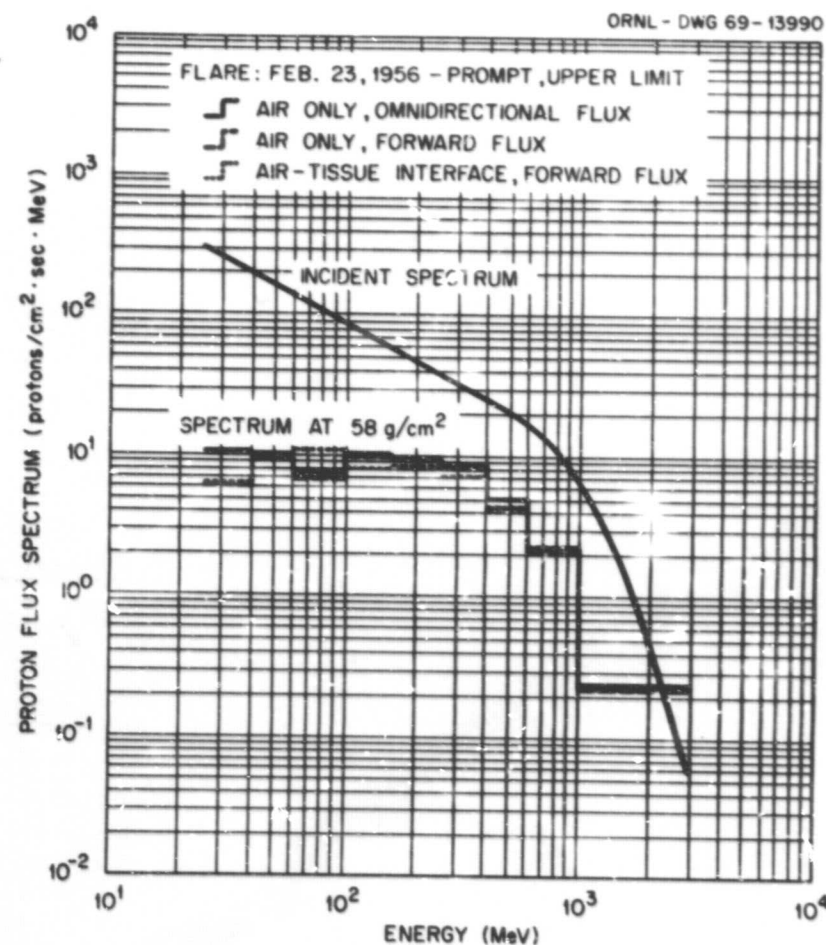
Fig. 5. Proton Flux Spectra at 58 g/cm². Also shown for comparison is the incident flux spectrum.
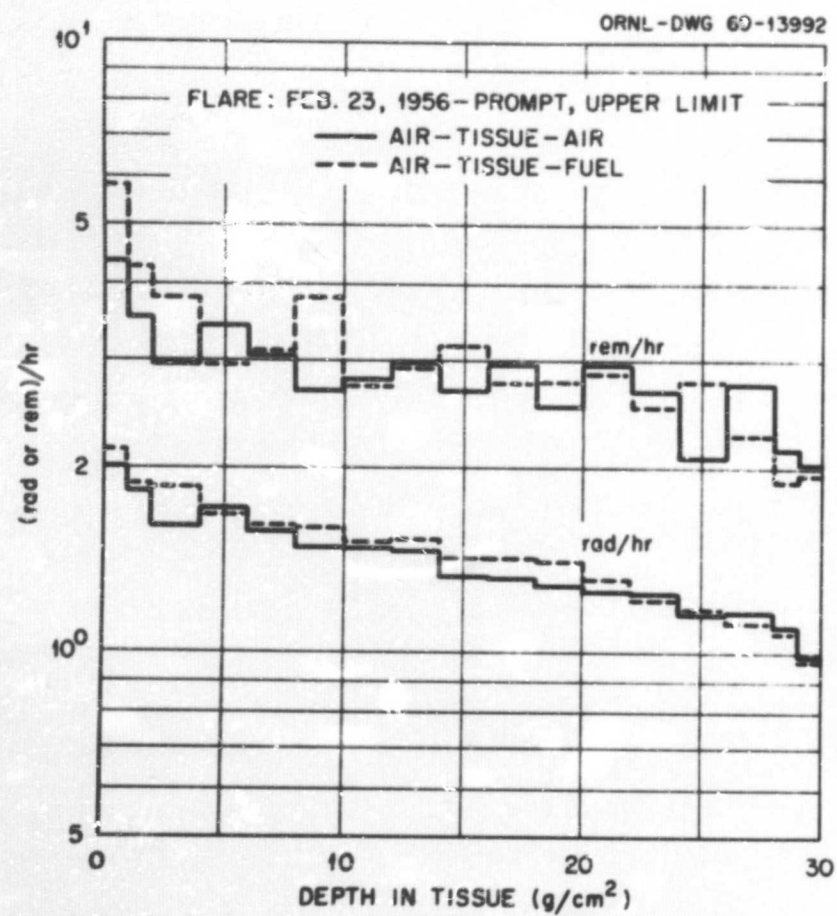
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Fig. 6. Spatial Distribution of the Dose Rate in the Tissue. The
fractional standard deviation of the histograms is ~ 10% and ~ 20% for the
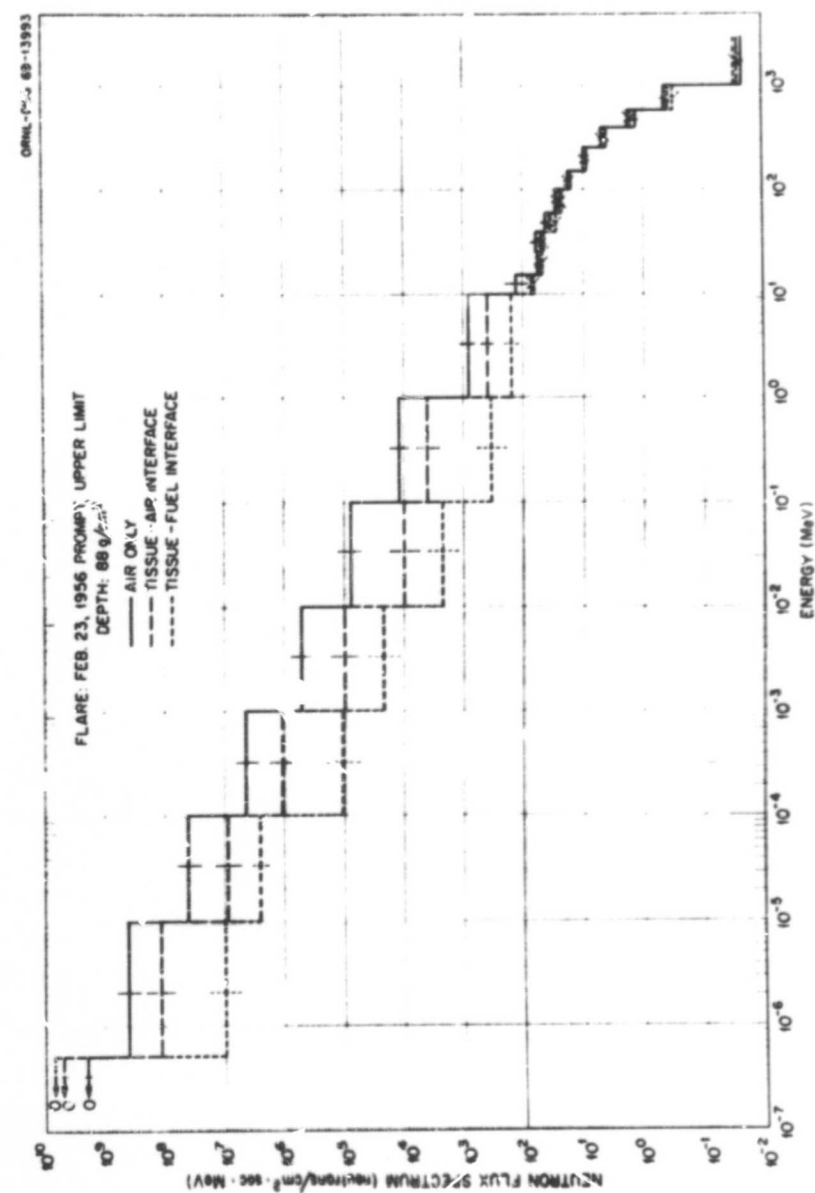absorbed-dose and dose-equivalent rates, respectively.

Fig. 7. Neutron Flux Spectra at a Depth of 88 g/cm².

little because of the small contribution of the low-energy neutrons to the dose.

Figures 8 and 9 give the contribution to the dose rate in the tissue according to particle type. The primary proton contribution is due to the ionization by those protons which have not experienced a nuclear interaction either in the air or in the tissue, and the secondary-proton contribution is due to the ionization produced by all other protons. The photon contribution includes those photons produced in the tissue by neutral-pion decay, nuclear de-excitation, neutron capture, and the annihilation of positrons resulting from muon decay. The heavy-nuclei (which here means all nuclei heavier than nucleons) contribution is due to the energy deposited by recoil nuclei from elastic and nonelastic collisions and by heavy evaporation products. The muons come from charged-pion decay and the electrons and positrons from muon decay. The photons, electrons, positrons, and heavy nuclei are assumed to deposit their energy at the point where they are produced; consequently, particles of this type which are produced in the air and enter the tissue are not included. In obtaining the dose equivalent, a quality factor of unity was used for photons, electrons, and positrons and a quality factor of twenty was assumed for the heavy nuclei. The quality factor as a function of energy for protons was taken from Turner et al.[11] for energies above 10 MeV and from Irving et al.[12] for lower energies. The quality factors for charged pions and muons were calculated from the proton quality factor. It is evident from Figs. 8 and 9 that while the proton contribution dominates the absorbed dose, the heavy nuclei are also important contributors to the dose equivalent because of their high quality factor.
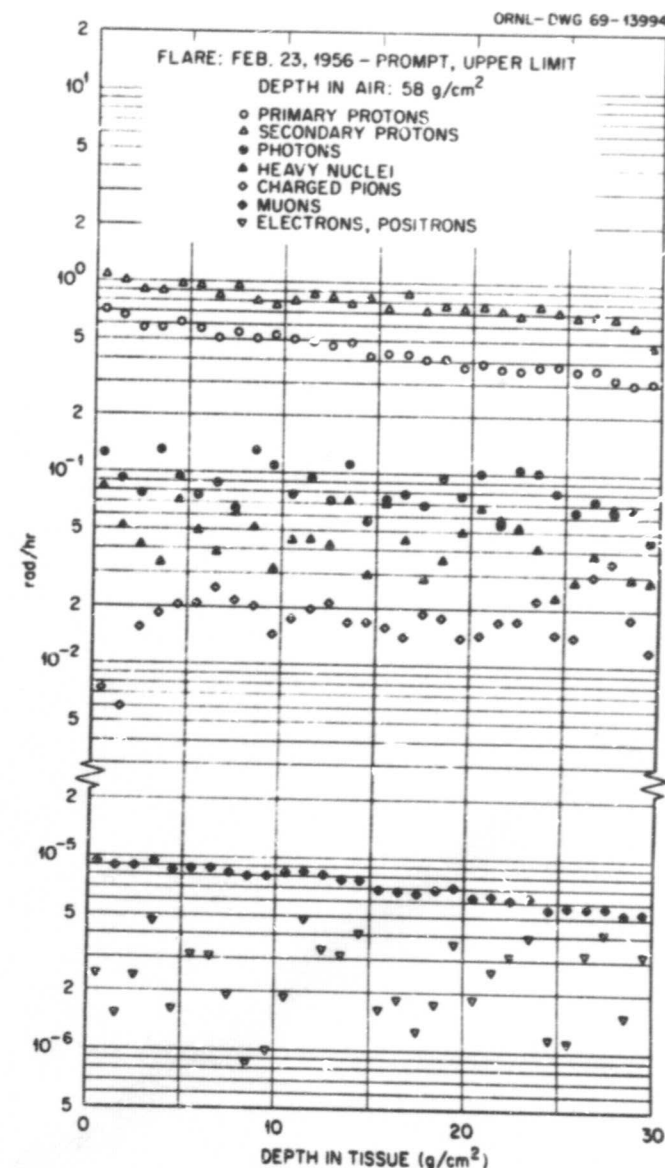
Fig. 8. Contributions to the Absorbed Dose in the Tissue According to Particle Type.
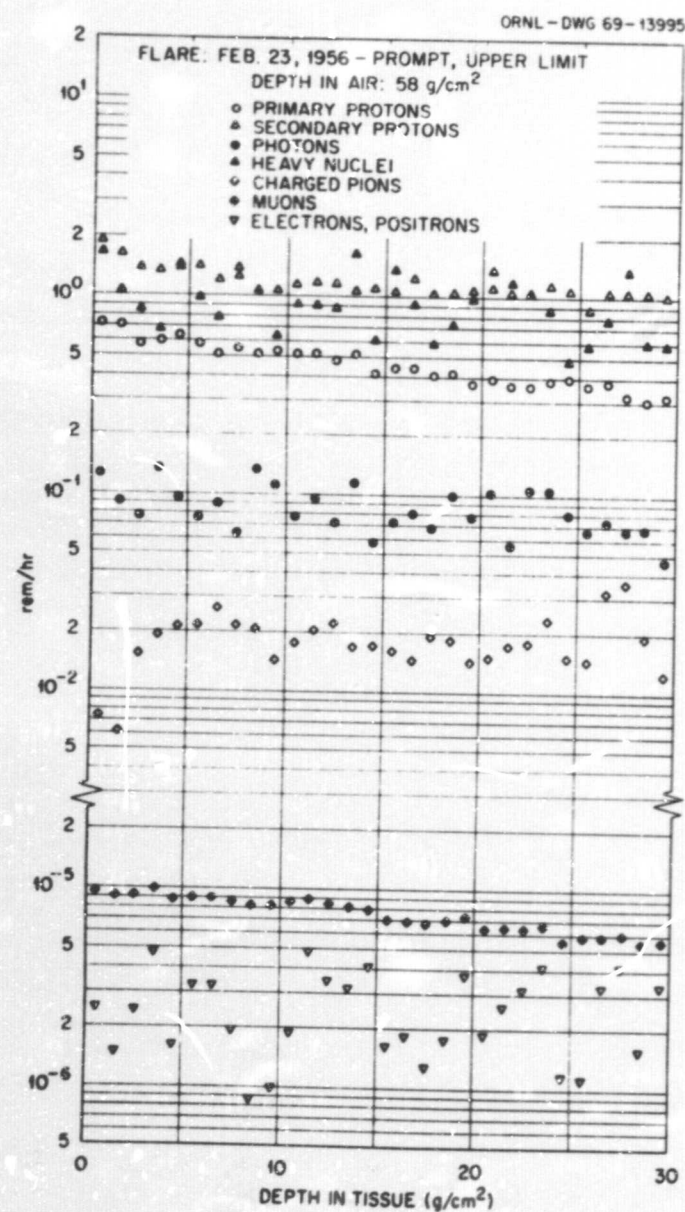
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Fig. 9. Contributions to the Dose Equivalent in the Tissue According to Particle Type.

In summary, the present calculations indicate that the dose rates given in paper 1 are considerable overestimates and that the results given here using the forward-flux spectra are better estimates. Using the forward-flux spectra calculated in air and flux-to-dose factors gives a very good estimate of the absorbed dose but overestimates the dose equivalent by ∿ 25%. This discrepancy is caused by using flux spectra calculated in air only which do not account for the flux perturbation that would occur if the tissue were actually present. Thus, if better accuracy is required, the tissue must be taken into account explicitly. Although the comparisons with and without the tissue are made at only one depth, the general conclusions should remain valid for other depths.

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FOOTNOTES

a. This work partially funded by the National Aeronautics and Space Administration (Order H-38280A) under Union Carbide Corporation's contract with the U. S. Atomic Energy Commission.

b. The flux-to-dose factors used are presented in paper 1 and are based on the data given by Zerby and Kinney[2] and Irving *et al.*[3] and in National Bureau of Standards Handbook 63.[4]

c. It should be realized that whether using the omnidirectional flux or the forward flux yields a better estimate of the dose in the tissue depends upon the thickness of the tissue. If the interest is in the dose produced in a very thin slab of tissue, then it would be expected that the omnidirectional flux would provide a better estimate since in this case the contribution of particles entering the "back" side of the tissue would also be important.

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